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THE CHARACTER AND AGE STRUCTURE OF VALLEY FILLS IN UPPER WOLUMLA CREEK CATCHMENT, SOUTH COAST, NEW SOUTH WALES, AUSTRALIA

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ABSTRACT

Extensive valley fills at the base of the escarpment in upper Wolumla Creek, on the south coast of New South Wales, Australia, have formed from a combination of 'cut and fill' processes. The valley fills comprise series of alternating, horizontally bedded sand and mud units, reflecting reworking of detritus from deeply weathered granites of the Bega Batholith. Sand units are deposited as sand sheets or splays on floodplain surfaces or in floodouts that form atop intact valley fill surfaces downstream of discontinuous gullies. Alternatively, sands are deposited from bedload and form bars or part of the valley floor within channel fills. Organic-rich mud units are deposited from suspension in swamps or in seepage zones at the distal margin of floodouts. Within 5 km ofthe escarpment, valley deposits grade downstream from sand sheet and splay deposition in floodouts, to mud deposition in swamp and seepage zones.

Radiocarbon dates indicate that virtually the entire valley fill of upper Wolumla Creek was excavated prior to 6000 years BP. Remnant terraces are evident at valley margins. The valley subsequently filled between 6000 years BP and 1000 years BP producing valley fills around 12 m deep, but no greater than 300 m wide. Reincision into the valley fill, on a scale smaller than the present incision phase, is indicated at around 1000 years BP, following which the channel refilled. Portion plans dated from 1865 refer to the study area as 'Wolumla Big Flat', and show large areas of swampy terrain, suggesting that the valley fill had re-established by this time. Within a few decades of European settlement the valley fill incised once more. Upper Wolumla Creek now has a channel over 10 m deep and 100 m wide in places, draining a catchment area of less than 20 km^2. © 1998 John Wiley & Sons, Ltd.

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KEY WORDS: valley fill; cut and fill processes; swamp sedimentation; floodplain; floodout; incision; gullying; human impacts

INTRODUCTION

Escarpment position and regional geology play critical roles in determining the character of rivers and their associated floodplains along the coastal plain of New South Wales (NSW). For example, there are significant differences in channel geometry and floodplain character for short coastal rivers of the Illawarra (Nanson and Young, 1981), bedrock-confined rivers of the Sydney Basin (e.g. Erskine, 1986), and some of the larger coastal river systems in the north of the state (e.g. Nanson, 1986; Warner, 1992; Brierley *et al*., 1995).

Extensive upland valley fills have formed at the base of the escarpment in granitic catchments along the south coast of NSW. These cut-and-fill landscapes reflect a balance between erosional and depositional processes. Over milennia, valley fill deposits are excavated as the escarpment retreats. Over shorter intervals these landscape compartments accumulate significant volumes of material. To date, the geomorphic and sedimentologic character of these valley fill deposits has largely been overlooked.

This paper describes the nature of valley fill deposits at the base of the escarpment in part of Bega catchment (Figure 1). Extensive valley fills, up to 12 m deep but no greater than 300 m wide, have formed in the upper reaches of Wolumla Creek, a north–south aligned subcatchment draining 90 km^2 in the southeast of the larger Bega catchment. The sedimentary character, nature of depositional processes, and age structure of the valley fill deposits are analysed.

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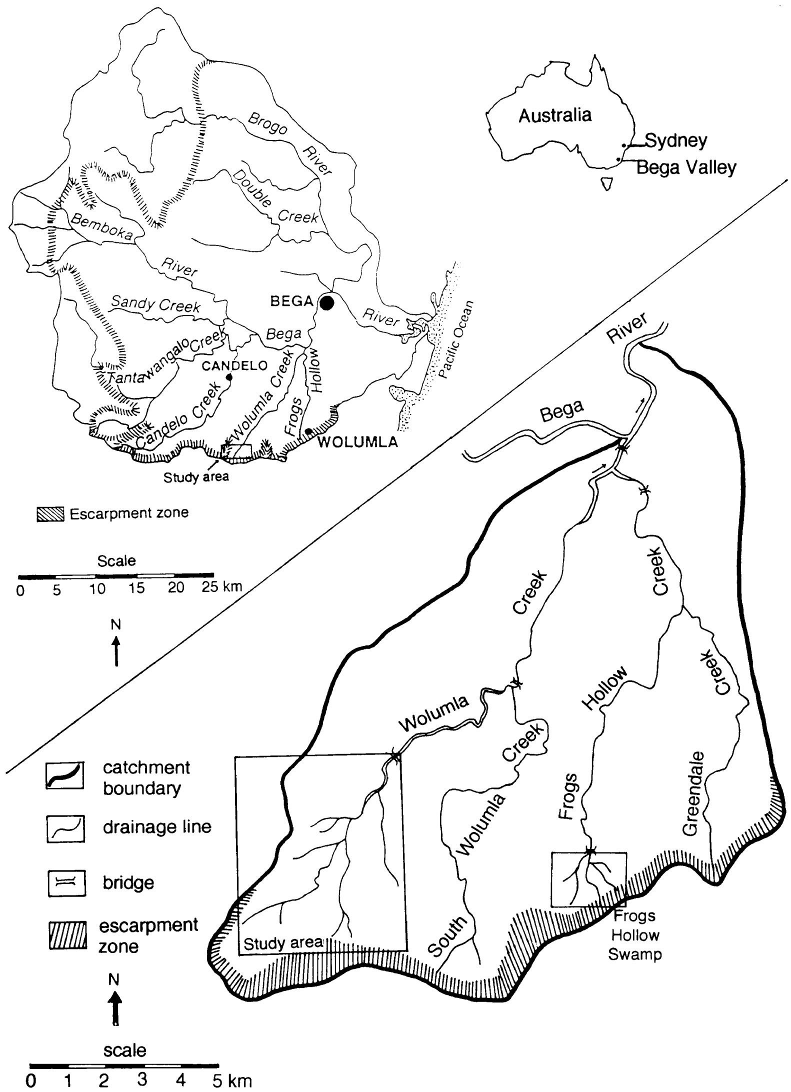

Figure 1. Location of Wolumla Creek, the study area and Frogs Hollow swamp. For a detailed map of the study area see Figure 2

REGIONAL SETTING

Located approximately 15 km south of Bega township, the study area comprises the upstream 18·2 km^2 of Wolumla Creek catchment (Figure 1). Significant breaks in slope are evident at the base of the escarpment and at the transition point between fan and valley fill sedimentation in upper Wolumla Creek (Figure 2). Adjacent to the valley flats, hillslopes have rounded, convex–concave morphologies with maximum slopes of 8–15° (Dixon and Young, 1981).

The valley fill stratigraphy reflects reworking of deeply weathered arenaceous mantles of granites and granodiorites of the Devonian Bega Batholith. Weathering products are distinctly bimodal in size, consisting of quartz and feldspar sands and kaolinitic clay (Dixon and Young, 1981). In Upper Anderson Creek, Devonian conglomerate and shale, with small amounts of sandstone, overlie the granite.

Average annual rainfall of the study area is 813 mm a^{-1} (1887–1995). The wettest year on record was 1934, with 1491 mm of rainfall, and 1904 was the driest with 356 mm. The largest flood on record occurred in 1971,

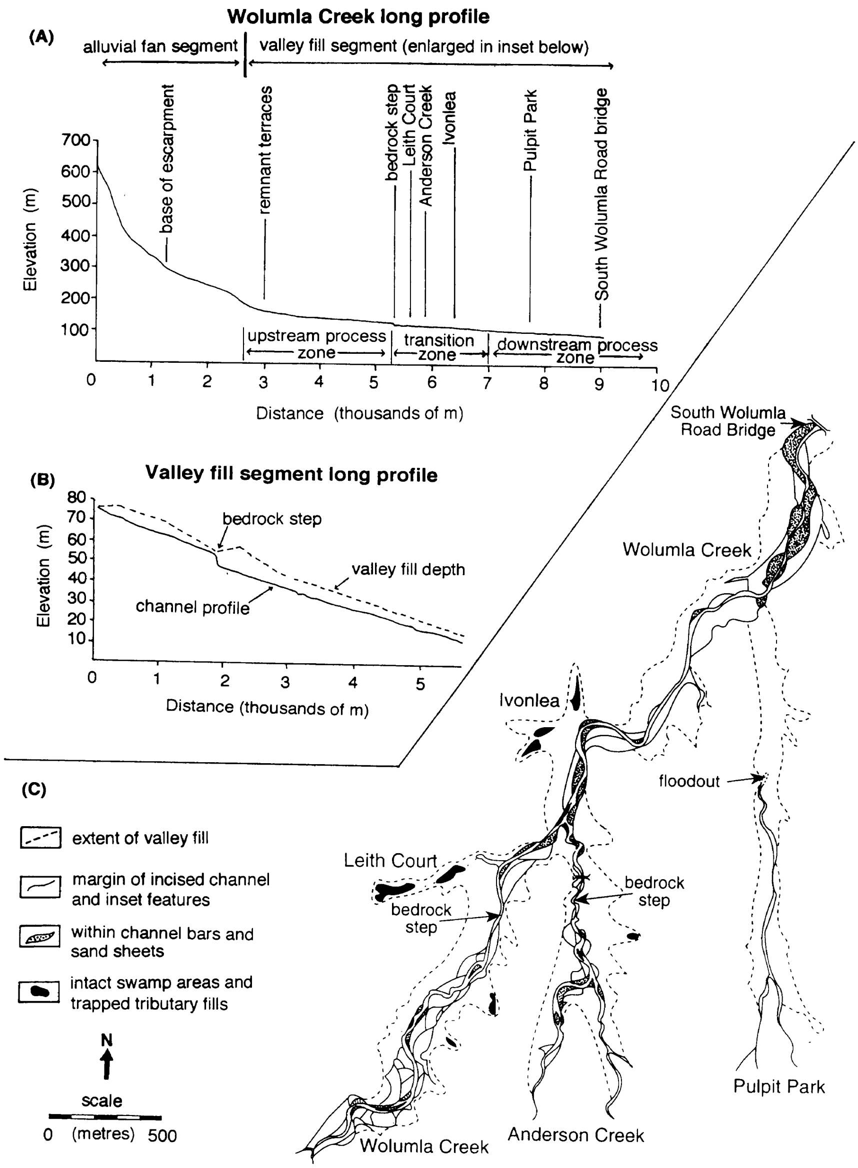

Figure 2. (A) Wolumla Creek long valley profile indicating the location of major tributaries, the alluvial fans at the base of the escarpment and the extent of the valley fill process zones. (B) Longitudinal profile of the valley fill segment of Wolumla Creek showing the thickness of valley fill along its length and the bedrock step. Solid line represents the channel long profile and the dashed line the depth of the valley fill. (C) Geomorphology of the study area. Note the discontinuous channel in Pulpit Park where a floodout is presently formed. Also note the greater complexity of insets and sand sheets in Wolumla Creek relative to Anderson Creek

where 324·9 mm of rain was recorded at Candelo on 6 February 1971. Winter months have the lowest average rainfall and summer/autumn the highest (Fryirs, 1995).

Wolumla is an Aboriginal name meaning ‘water hole’ (Wolumla Centenary Committee, 1982). Other than Aboriginal occupation, the area surrounding Wolumla was first settled in 1851. Creek lines were claimed by the primary landowners and hillslopes were divided amongst selectors. The area upstream of Pulpit Park (Figure 2), which incorporates the majority of the study area, was settled after 1861. The 1865 portion plans show that the valley floor was occupied by ‘Wolumla Big Flat’. Water was ‘always attainable’ in these open, well-grassed swamps (1865 Portion Plan nos 595_{1572} and 196_{1438}). Soon after settlement, the valley flats and adjacent

(a)

(b)

(c)

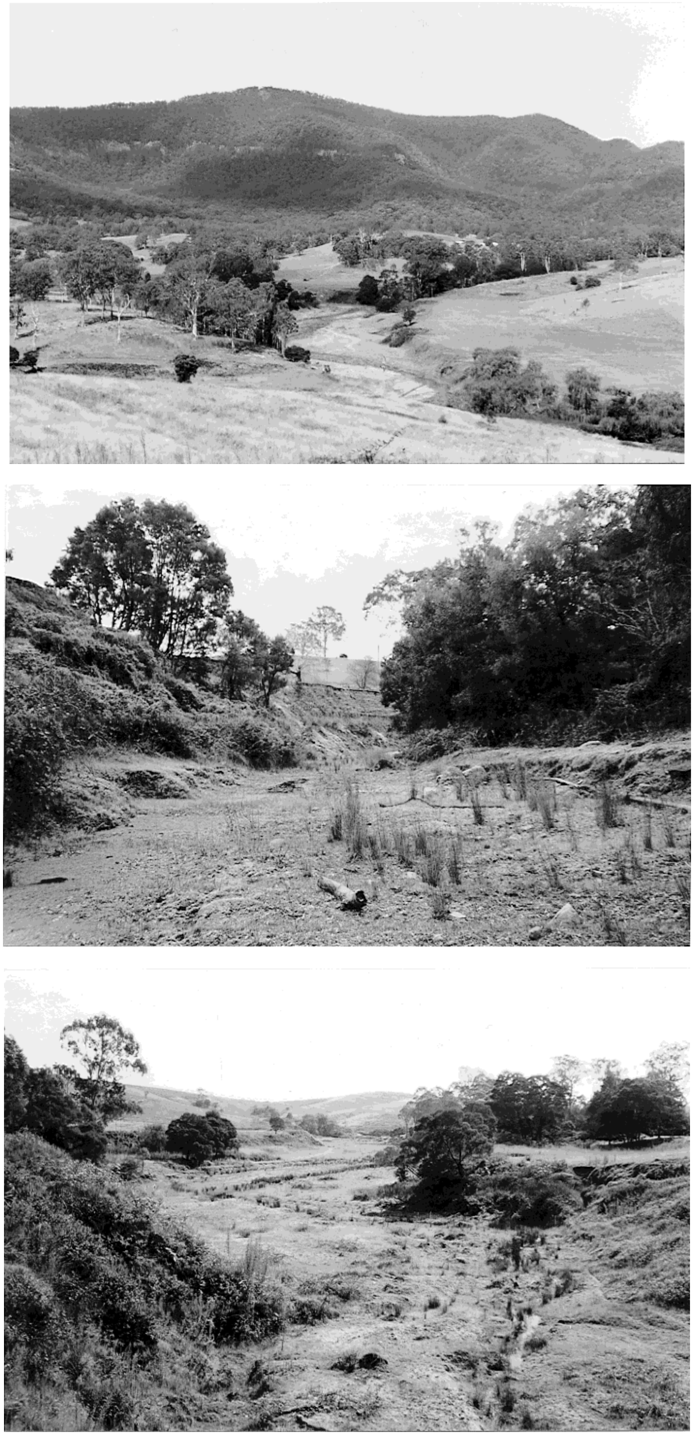

Figure 3. (a) Oblique photograph of Wolumla Creek (foreground) extending to the Anderson–Wolumla confluence (middle ground), and the escarpment (background). Note the extent of the enlarged channel incised into the valley fill and the steepness of the escarpment in upper reaches of the catchment. The incised channel in the foreground is 7 m deep and 95 m wide. (b) Ground shot of enlarged incised channel in Wolumla Creek. This photograph is looking downstream from the bedrock step. The bank exposure in the background (W3) is 12·7 m deep. (c) View downstream from Anderson–Wolumla Creek confluence. Note how the width of Wolumla Creek increases markedly from (b) (located just 120 m upstream); (a) was taken looking upstream from the hill in mid-photograph

hillslopes were cleared, swamps were drained and cultivated, and access roads were cut across the flats. Anecdotal evidence suggests that incision into Wolumla Big Flat began around 1900 (J. McPaul and W. Dunning, 1995, pers. comm.), while incision into Anderson Creek tributary, which was a small ditch across which a horse and cart could safely cross prior to 1938, occurred between 1938 and 1944 (Figure 2; K. Anderson, 1995, pers. comm.). Air photographs indicate that incision into the upper part of both Anderson and Wolumla Creeks was well established by 1944. Anderson and Wolumla valley fills are now deeply incised by a channel over 10 m deep and up to 100 m wide (Figure 3).

Today, around 60 per cent of the study area consists of open sclerophyll forest, which dominates the escarpment zone and the steep terrain of Yurammie State Forest. The remainder of Wolumla Creek catchment is covered by native and introduced pasture lands.

SEDIMENTARY CHARACTER OF VALLEY FILLS IN UPPER WOLUMLA CREEK

Fourteen valley fill bank exposures, up to 60 m long and 12·7 m deep, were analysed in upper Wolumla Creek and Anderson Creek (Figure 4). Depth to bedrock generally extended more than 2·0 m below the channel bed. Exposures are aligned longitudinally, and no lateral exposures enable the three-dimensional geometry of depositional units that comprise the valley fill to be discerned.

Valley fill deposits comprise alternating sequences of organic-rich mud and sand units, separated by abrupt, near-horizontal boundaries (Figures 4 and 5a). While units are laterally continuous within bank exposures, they do not correlate between exposures which are as little as 30 m apart or on opposite sides of the incised channel.

Before characterizing the downstream variability of valley fill stratigraphy, the character of the mud and sand units is outlined.

Mud units

Mud units comprise cohesive, very fine sands, silts and clays. Sedigraph results indicate that most units have a median grain size diameter less than 1 μm. Ranging in thickness from 2 to 177 cm, most mud units are massive, but some units are horizontally laminated. Colour ranges from brownish grey (7·5YR 6/1) to black (7·5YR 1.7/1). Charcoal and organic matter are abundant, with percentages of organic matter on ignition ranging from 11 to 29 per cent depending on the extent of preservation of bark and other plant remains. The only evidence of bioturbation within mud units is the presence of earthworm castings in some units and root casts/casings throughout most units. Preliminary phytolith analysis showed that mud units contain abundant *Poaceae* spp., but *Cyperaceae* spp. are absent (Fryirs, 1995). No positive identification of macrofossil plant remains was possible due to the highly degraded nature of the material, but *Melaleuca* sp. bark is thought to be present (Fryirs, 1995). The level of soil development is poor throughout all exposures and on valley fill surfaces, with minimal organic coloration in many profiles, no textural or colour contrasts, no sign of horizonation and only occasional ped development. All materials displayed a strong degree of inheritance from primary fluvial deposition, suggesting that the rate of sediment accumulation and/or redistribution exceeded the rate of pedogenic alteration.

The character of the mud units indicates that they were deposited from suspension in a vegetated environment, during periods when the valley fill was intact. A proposed analogue for these deposits was analysed in an intact tea tree swamp in an adjacent catchment. Upper Frogs Hollow swamp, approximately 6·2 km to the east, has similar geology, geomorphic setting, and climate to the study area (Figure 1). A distinct pattern of vegetation associations still exists in upper Frogs Hollow, despite vegetation clearance and cattle grazing (Fryirs, 1995). Sediments of Frogs Hollow swamp are characterized by alternating organic-rich mud units and sand units, with considerable cross-valley variability in the stratigraphy (Figure 6). Mud units are generally thinner (<100 cm) than sand units (>100 cm) and the sands are primarily medium to coarse in grain size (0·25–1·0 mm). Mud units contained *Poaceae* sp. phytoliths and some contained macrofossil remains, while most contained rootlets throughout.

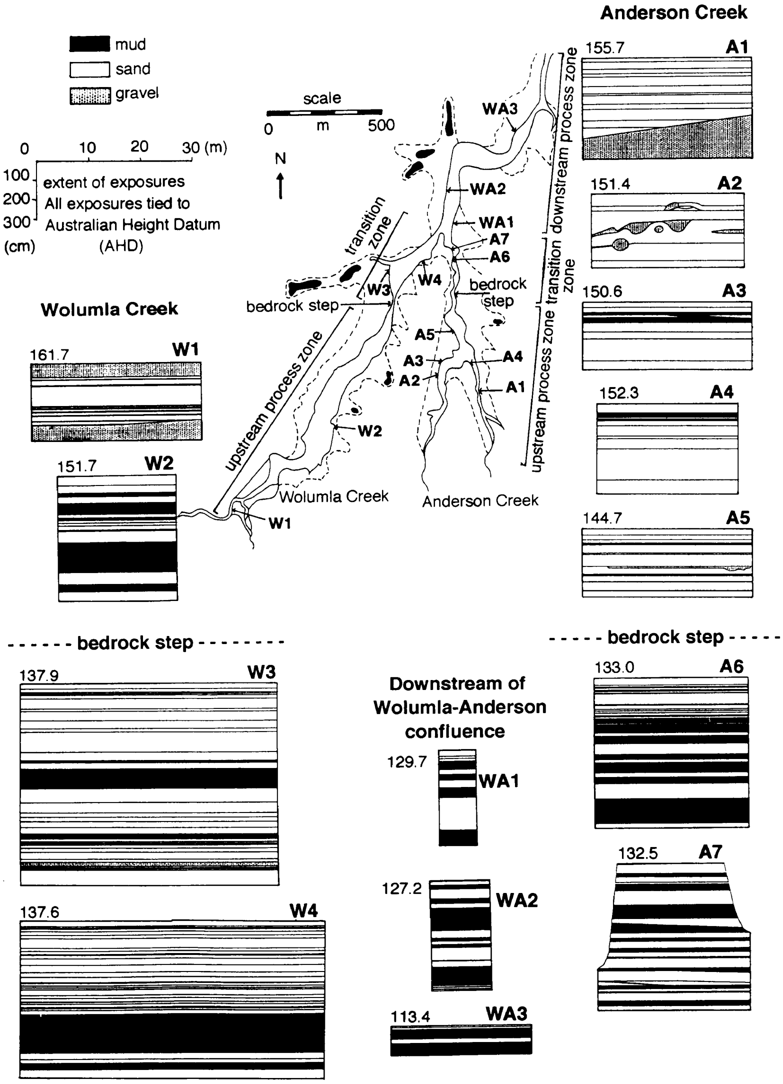

Figure 4. Downstream sequence of bank exposures showing valley fill sedimentary character. Note the variable character of sediment types upstream and downstream of the bedrock step and the discontinuity of sediment assemblages in adjacent exposures

Sand and gravel units

Sand units in upper Wolumla Creek valley fills range in texture from very fine sands to very coarse sands (0·0625–1·41 mm). Bed thickness is highly variable, ranging from 2 to 277 cm. Some units are horizontally bedded, others have planar or trough cross-beds, but most units are massive, with no internal structure or textural grading. Sand units are typically dull yellow orange (10YR 7/2) to dull brown (7·5YR 5/4). In general, charcoal fragments are only found in finer-grained sand units. Gravels are seldom observed in bank exposures, their presence restricted to occasional basal units in three channel fills. These gravel layers range in thickness from 5 to 30 cm with grain sizes up to 70 mm (*b*-axis) in a matrix of coarse sands (0·5–0·71 mm). The channel fills themselves extend up to 310 cm wide and 75 cm deep. The basal parts of exposures in upper Anderson and Wolumla Creeks comprise imbricated gravel and occasional boulders up to 700 mm (*b*-axis) with a very fine sand matrix (0·088–0·125 mm). The boulders, which are generally subangular to subrounded, may have been deposited by debris flows. Gravel lags, ranging in size up to 270 mm (*b*-axis), line the present creeks.

(a)

(b)

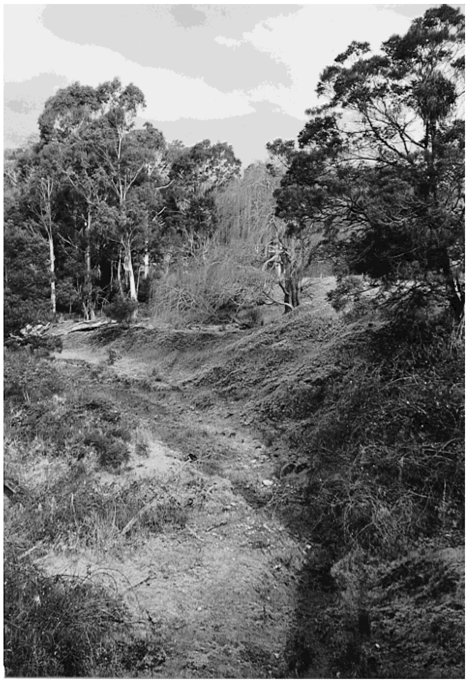

Figure 5. (a) Bank exposure W3 showing the horizontally bedded alternating sands and organic-rich mud units which characterize the valley fills. This bank exposure is 12·7 m deep and was noted in Figure 3b. (b) Example of an inset feature within the valley fill. These features are accretionary, not erosional as they have sedimentologically distinct boundaries with the main valley fill. This particular inset is exposure Ac in Figure 8. The inset is 3·8 m deep and the incised channel is 45 m wide and 9 m deep

While most sand units probably reflect deposition as sand sheets on floodplains, other evidence suggests that a significant proportion of valley fill deposits formed from sand sheet and splay deposition in floodouts, which occur downstream of the intersection points on the long profile of discontinuous gullies (cf. Erskine and Melville, 1983). There are numerous active knickpoints in upper Wolumla Creek, reflecting these discontinuous gullying processes (Fryirs, 1995). While sand sheets or splays form downstream of intersection points, fines are flushed further downstream or accumulate in seepage zones.

A direct analogue for floodout deposition is evident in Pulpit Park, the subcatchment immediately to the east of Anderson Creek (Figures 2 and 7). Up-valley sections of the channel incised into Pulpit Park valley fill extend up to 8 m deep and 5 m wide. The channel widens to 13 m downstream, but depth decreases, and the

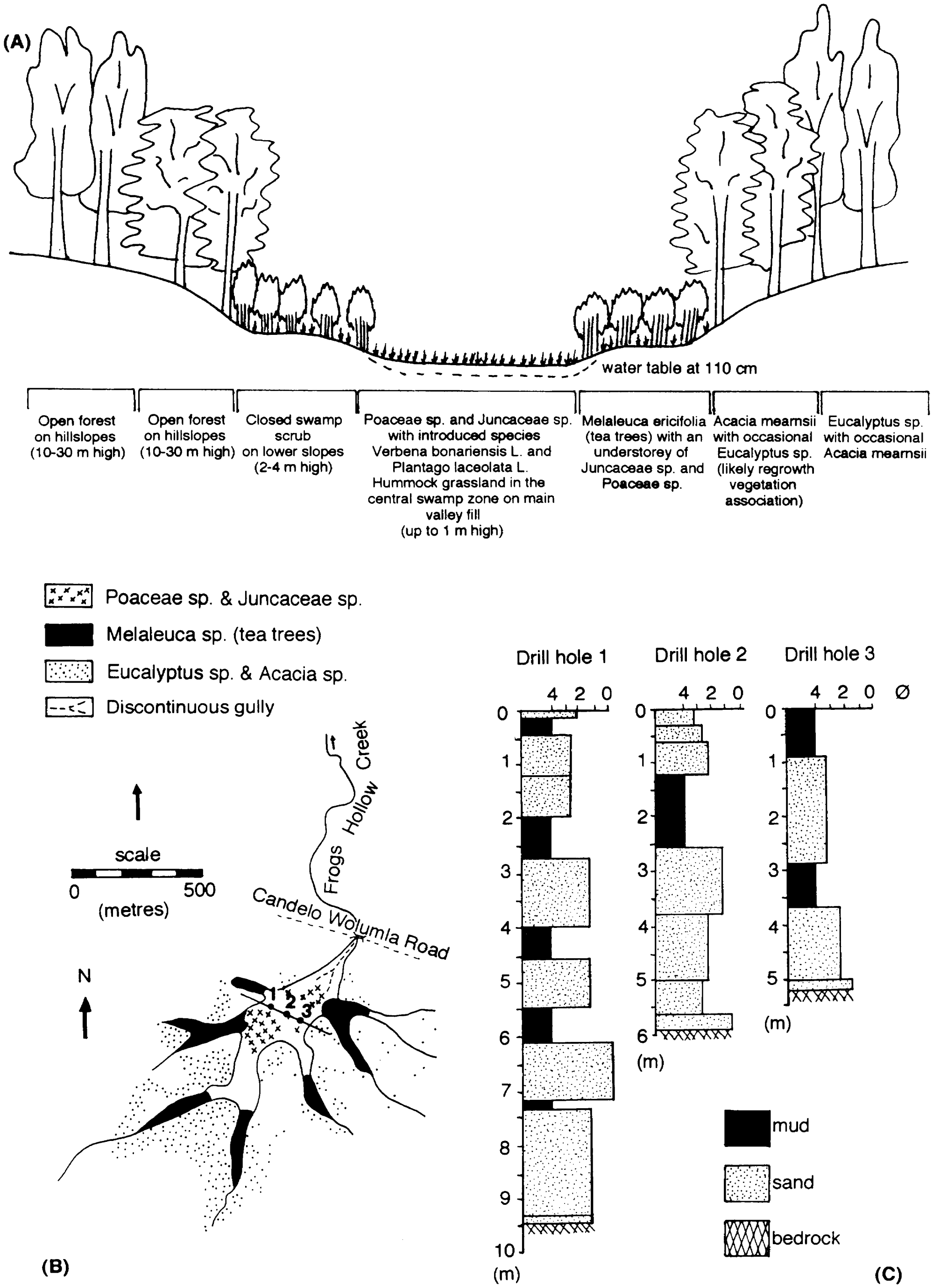

Figure 6. Frogs Hollow swamp (for location see Figure 1). (A) Schematic cross-section showing vegetation associations (Specht, 1981; Briggs, 1981). (B) Planview of swamp showing vegetation associations and the location of drill holes 1, 2 and 3. (C) The cross-valley sedimentary character of Frogs Hollow swamp

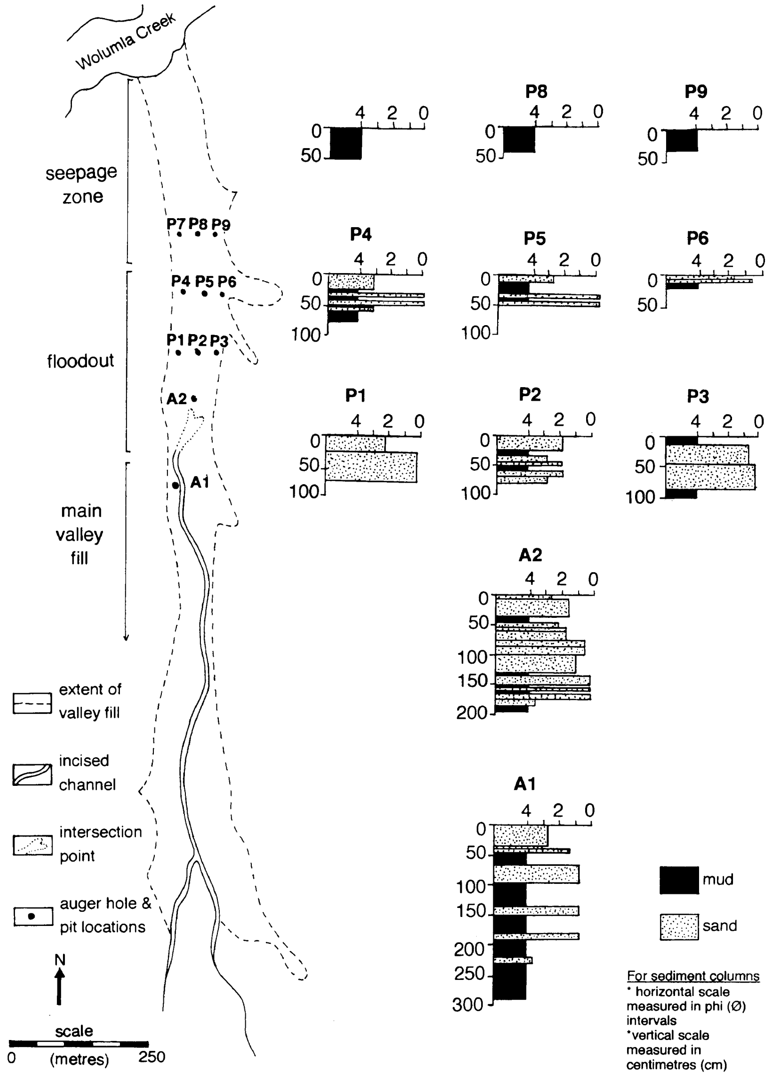

Figure 7. Cross- and down-valley sedimentology of Pulpit Park main valley fill, floodout and seepage zone

channel terminates at an intersection point, beyond which flows and deposits are spread over the valley floor to produce a floodout (cf. Erskine and Melville, 1983). Slope decreases downstream from around 0·032 on the main valley fill to 0·014 on the floodout. The floodout has a convex cross-profile and extends for approximately 300 m downstream from the intersection point. Beyond the floodout, a seepage zone extends to the confluence with Wolumla Creek.

The main valley fill of Pulpit Park subcatchment (sediment column A1 on Figure 7) comprises irregularly interbedded sand and mud units. In general, mud units are thicker (up to 60 cm) than the sand units (<35 cm thick). Within the floodout, sand units thin downstream to around 5–10 cm, whereas mud units thicken from around 5 cm thick at the head of the floodout to units which are up to 20 cm thick immediately upstream of the seepage zone. The seepage zone itself is characterized solely by an organic-rich mud unit that is at least 50 cm thick.

Floodout development reflects initiation of discontinuous gullying in response to local oversteepening of the valley floor (Schumm *et al.*, 1984; Melville and Erskine, 1986), or local weakening of surface vegetation (Schumm *et al.*, 1984; Prosser *et al.*, 1994; Prosser and Slade, 1994). The variable stratigraphy of the floodout,

Table I. Sediment characteristics of process zones in upper Wolumla Creek valley fills

Zone	Sediment composition	Mean valley width (m)	Mean valley flat width (m)	Mean channel width (m)	Mean channel depth (m)	Valley flat slope	Channel slope
Upstream process zone (upstream of bedrock step)	Little or no alternation between sand and mud units. Thick sand units dominate the fill stratigraphy, often stacked atop one another.	152·9	95·9	57·0	4·1	0·041	0·018
Transition zone	Significant alternation between sand and mud units throughout the fill.	264·1	181·3	82·8	10·0	0·026	0·010
Downstream process zone (downstream of confluence)	Little or no alternation between sand and mud units. Thick mud units dominate the fill stratigraphy, often stacked atop one another.	234·0	100·0	134·0	5·3	0·024	0·009

both down-valley and cross-valley, suggests that deposition of sand units occurs in shifting lobes along dominant drainage lines. Continual adjustment in floodout margins results in large numbers of abrupt boundaries between mud and sand units, and a lack of erosional scour at the contacts.

Downstream variability in sediment composition of the upper Wolumla catchment valley fills

At the base of the escarpment, valley fill deposits in upper Wolumla catchment overlie the downstream margin of fan deposits, and are inset within valley-marginal terrace remnants. The character of valley fill deposits can be divided into three segments, namely upstream of bedrock steps in Wolumla and Anderson Creeks (upstream process zone), the sections between the bedrock steps and Wolumla–Anderson confluence (transition zone) and downstream of the confluence (downstream process zone) (Figure 4; Table I).

In the headwater valley fill of Anderson Creek (exposure A1; Figure 4), thinly interbedded (<70 cm thick) sands lie atop clast and matrix-supported gravels. In contrast, sands (up to 125 cm thick) alternate with thin mud units (typically <10 cm thick) atop a gravel base in upper Wolumla Creek (exposure W1). These gravel units in both Anderson and Wolumla Creeks represent the downstream extent of alluvial fans. In Anderson Creek, four further exposures (A2–A5) upstream of the bedrock step are characterized by horizontally bedded sands, up to 200 cm thick, which make up over 85 per cent of each exposure. Interbedded mud units are typically thin (<35 cm). In exposure A2, gravelly channel fill units are observed, while mud units are absent. Mud units are restricted to the upper 1·5 m in exposures A3 and A4, but are interspersed with thinner sand units throughout exposure A5. The only other exposure analysed above the bedrock step in upper Wolumla Creek (exposure W2) is thinly interbedded and contains a significantly higher proportion of mud units (around 45 per cent) relative to exposures upstream of the bedrock step in Anderson Creek.

The limited representation of mud units in headwater valley fill exposures suggests that swamps rarely extended to the base of the escarpment and only developed during the later stages of valley fill aggradation. Sand sheets and splays deposited on floodplains or in floodouts have been selectively stored in relatively thick, stacked units behind bedrock steps (Figure 2), while muds have been flushed downstream. Swamp development only occurred once the influence of the bedrock step was diminished following its burial. Hence, mud units are restricted to higher sections of the exposed valley fill (for example in exposures A3 and A4). The exception to this scenario, exposure W2, is located approximately 900 m upstream of the bedrock step. This site is considered to be far enough upstream to negate the influence of the bedrock step, and swamps formed in this wider section of the valley (valley width of 230 m) during earlier stages of valley fill aggradation.

Downstream of the bedrock step, the proportion of mud units increases markedly to around 20 per cent in Wolumla Creek and around 45 per cent in Anderson Creek (exposures W3 and W4, A6 and A7 respectively). While mud units thicken downstream of the bedrock step (up to 280 cm in Wolumla Creek, and up to 90 cm in Anderson Creek), sand units thin to <100 cm. In contrast to upstream reaches, where mud units are generally

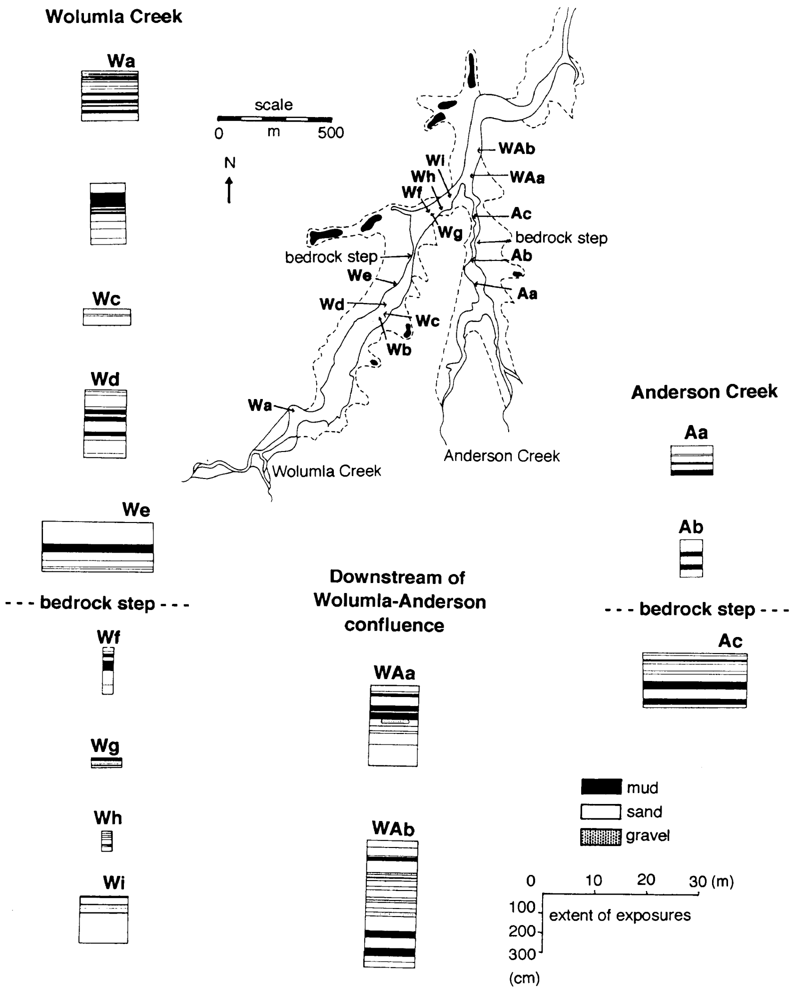

Figure 8. Downstream sequence of inset features showing sedimentary character. These inset features do not necessarily represent equivalent levels

restricted to the upper section of exposures, mud units are interspersed throughout the valley fill, with over 25 bedded units in each exposure. Rather than reflecting temporal variability in the availability of materials of particular size, or the varying competence of flow to transport materials of differing calibre, this probably reflects spatial variability in depositional process associated with swamp and seepage zone processes (as observed in Frogs Hollow swamp, Figure 6) punctuated by shifting lobes of sand sheet deposition on floodplains or floodouts (as exemplfied by Pulpit Park floodout, Figure 7).

Downstream of Wolumla–Anderson Creek confluence, the valley is narrower and valley flat slopes are gentler (less than 0·027; Table I). Bank heights reduce to between 2 and 7 m. Thick mud units have accumulated in swamps and seepage zones, reflecting selective downstream flushing and sorting of materials. Bedload deposition only occasionally disrupts swamp aggradation when floodout depositional lobes or sand sheets on floodplains extend downstream during large flood events, depositing relatively thin sand units atop mud. The extreme downstream exposure analysed in the study area, Site WA3, consists of around 75 per cent mud material with thick (around 60 cm), stacked mud units and only occasional sand units (up to 25 cm thick).

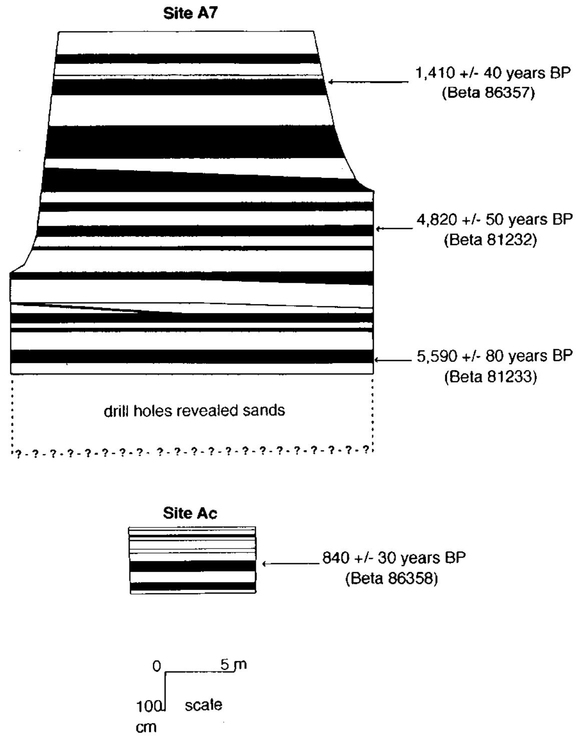

Figure 9. Location of the materials dated from the main valley fill and inset feature in Anderson Creek

In summary, upper Wolumla valley fills grade in a downstream sequence from stacked thick sand units in the upstream process zone to alternating sequences of sand and mud units in the transition zone, and finally to stacked thick mud units in the downstream process zone. Mud beds increase in thickness downstream, while the thickness of sand beds decreases.

Sediment composition of inset features

Landforms deposited within the enlarged incised trench represent fill features which have subsequently been reincised to leave a perched feature above the present channel bed. Up to four inset levels are evident, ranging in height from 1·0 to 6·5 m above the channel bed. These units reflect the complex history of cut-and-fill processes in this landscape. Since Wolumla Creek is broader than Anderson Creek, it has a more intricate spatial distribution of inset features. Sedimentological analysis of 14 inset features shows that these are accretionary forms within the main incised channel rather than erosional landforms (Figures 5b and 8). The proportion of sand and gravel within inset features increases downstream, reaching >80 per cent downstream of Wolumla–Anderson confluence. In general, inset units are coarser-grained than adjacent valley fill exposures. This reflects more effective downstream flushing of muds within the confined incised channel relative to deposition on flat, vegetated, valley fill surfaces.

AGE RELATIONSHIPS IN THE UPPER WOLUMLA CREEK VALLEY FILL

Although significant difficulties exist in interpreting the ‘true age’ of fluvially reworked charcoal samples (see Blong and Gillespie, 1978; Gillespie *et al.*, 1992), these materials provide the most readily available samples for dating valley fill deposits in upper Wolumla Creek (Fryirs, 1995). A large quantity of charcoal from a basal mud unit at Exposure A7, about 9 m from the valley fill surface and approximately 2·5 m above bedrock, yielded a radiocarbon age of 5590 +/−80 years BP (Beta 81233; Figure 9). Two further charcoal samples, collected

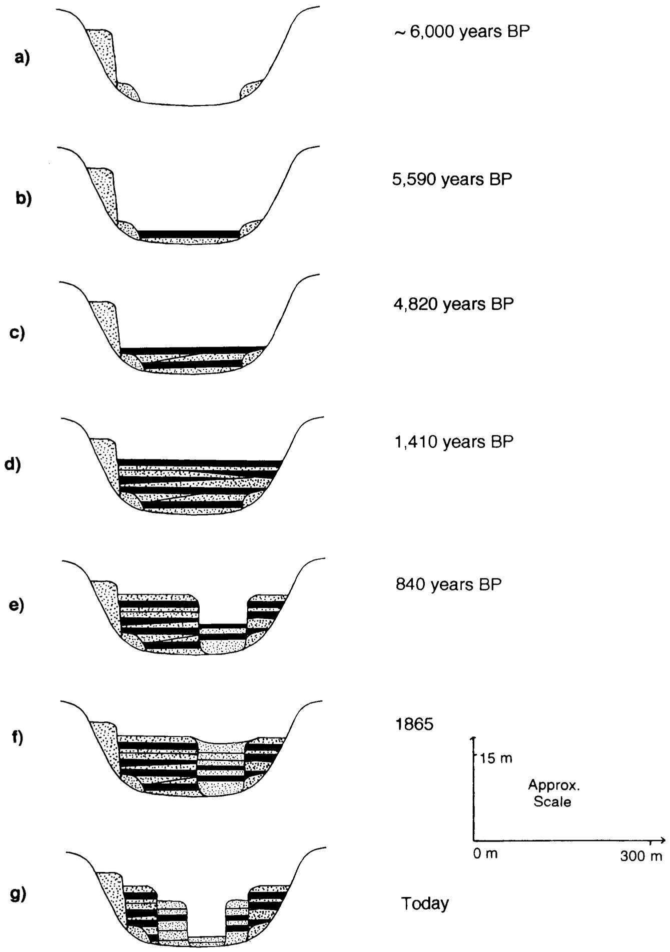

Figure 10. Schematic evolutionary model for the development of valley fills in upper Wolumla Creek, 6000 years BP to present. (a) At around 6000 years BP relict terraces are perched up to 12 m above the valley floor and fragments of older valley fill, not removed by the valley flushing episode, remain at the valley margins. (b) Valley fill deposits begins to fill the valley floor. (c) By 4820 years BP 3·4 m of valley fill has aggraded via alternating phases of sand and organic-rich mud deposition. (d) By 1410 years BP the valley fill has almost reached its contemporary level. (e) By 840 years BP a narrow, deep channel has incised the valley fill and 3·8 m of channel fill material has been deposited. (f) In 1865 the valley fill is intact and noted as 'Wolumla Big Flat' on portion plans. (g) Since 1900 a deep, wide channel has incised the valley fill and today the channel is characterized by inset features and bed aggradation

from mud units at 5·5 and 1·3 m from the valley fill surface, in the same exposure, yielded ages of 4820 +/– 50 years BP (Beta 81232) and 1410 +/– 40 years BP (Beta 86357) respectively.

Considering the coarse sand composition of units in the basal 2·5 m of Exposure A7, it is inferred that these deposits accumulated quickly and that valley fill aggradation began around 6000 years BP. Fragments of older valley fill at valley margins, and remnant terrace units perched 2 m above the maximum contemporary level of valley fills (i.e. 12 m above the channel bed) testify to phases of extensive sediment removal before 6000 years BP. The patchy preservation of these deposits attests to the effectiveness of removal processes in this confined, high-energy setting. It cannot be inferred that the flushing phase immediately predated 6000 years BP, only that valley floor aggradation recommenced at about that time. This is presented as the initial stage in a model of valley fill evolution of upper Wolumla Creek in Figure 10a.

Valley flushing prior to 6000 years BP may be climatically related, as there is seeming accordance with commencement of valley floor aggradation after this date elsewhere in coastal New South Wales, e.g. Wollombi Brook and Colo River (Hickin and Page, 1971), Macdonald River (Blong and Gillespie, 1978),

Fernances Creek (Melville and Erskine, 1986) and Bellinger River (Warner, 1992). Bowler *et al*. (1976) and Dodson (1987) report that in the last 5000 years there has been little significant change in the climate of southeastern Australia, with only minor oscillations in temperature and rainfall. However, palaeoclimatic indicators point to a 'slightly wetter period' between 8000 and 5000 years BP (Dodson, 1986). Although this is not considered to be a significant climate change (the move to more ephemeral conditions is suggested to be only slight), this may have had significant impact on ground cover, especially if this coincided with an increase in the frequency of fire. Reduced vegetation cover and increased ground erosivity would increase the effectiveness of flood events, potentially triggering incision of valley fills and removal of large volumes of material (cf. Prosser and Slade, 1994).

Available radiocarbon dates infer that between 5600 and 4800 years BP, 3·4 m of valley fill sedimentation occured (Figure 10b and c), whereas by around 1410 years BP the valley fill was roughly 1·5 m lower than the contemporary valley fill surface (the maximum fill level preserved over the last 6000 years; Figure 10d). Significant reworking of valley fill deposits probably took place in this period of valley fill aggradation, as evidenced by small channel fills in bank exposures along Anderson and Wolumla Creeks.

Approximately 25 m upstream of Exposure A7, charcoal fragments from a mud unit halfway up a 3·8 m high inset feature yielded an AMS age of 840 +/− 30 years BP (Beta 86358; Exposure Ac on Figures 8 and 9; Figure 10e). The inset feature largely comprises sands, but there are two fairly thick (around 35 cm) mud units in the lower half of the feature. From this, it is suggested that the contemporary valley fill surface was attained around 1000 years BP. Subsequent channel incision proceeded rapidly to bedrock (cf. Prosser *et al*., 1994). This was followed by a phase of refilling by coarse sands and occasional muds. Rates of aggradation of deposits refilling the incised channel would be much greater than rates of valley fill aggradation, given the smaller width.

On the 1865 portion plan, the valley fill was noted as 'Wolumla Big Flat', indicating that the process of incised channel infilling was complete, and that the system was unincised at this time (Figure 10f). This intact valley fill has been transformed dramatically in the period following European disturbance of the area. Since around 1900 in Wolumla Creek and the early 1940s in Anderson Creek, a wide, deep channel has incised to bedrock via knickpoint migration. Mobilization of large volumes of material within this channel resulted in the formation of insets along the channel margins (Figure 10g). The reduction of surface vegetation of 'Wolumla Big Flat' and surrounding hillslopes, together with drainage and cultivation of the flats, played a significant role in initiating the present episode of valley fill incision. No direct evidence is available to discern what event or events resulted in the initiation of discontinuous gullying into the valley flats of upper Wolumla Creek. However, circumstantial evidence indicates that incision may have been initiated at a track that cut across the flats. Little evidence exists for significant local climate change around this period (Brooks, 1994; Kirkup, 1996). However, a number of large magnitude flood events occurred at the end of the last century, possibly accentuated by altered runoff relations within the catchment (Brooks and Brierley, 1997, in press). Human disturbance of the flats, during this period of large magnitude flood events, probably forced the intrinsic slope thresholds to be exceeded, in turn triggering the post-settlement incision phase.

Incision and lateral expansion of the channel proceeded rapidly, probably within a few decades of disturbance (Brierley and Fryirs, in press). Indeed, aerial photographs from 1962 to 1994 indicate little recent change in the geomorphic character of upper Wolumla Creek catchment. The geomorphic effect of the flood of record in February 1971 was insignificant. In the period following incision and lateral expansion of the channel, up to 2·5 m of coarse bedload materials have accumulated atop the bedrock floor. This, together with large volumes of coarse bedload material stored in inset features, could attest to partial refilling of the system.

DISCUSSION

A range of cut-and-fill floodplain types have been described for high-energy upland settings. Examples of these upland valley fills, referred to as floodplain type A4 in Nanson and Croke (1992), include swampy meadows (Prosser, 1991; Prosser *et al*., 1994), dells (Young, 1986), chains of ponds (Eyles, 1977), swamplands (Bird, 1982) and dambos (Mackel, 1974). A combination of lithologic and topographic controls has ensured that the material character and composition of the floodplains described in this manuscript differ from the upland valley fills described elsewhere.

Valley fills in upper Wolumla Creek formed downstream of a significant break in slope which demarcates the valley floor from the escarpment. The granitic lithology, along with topographic controls exerted by the escarpment and base level control at bedrock steps, has exerted considerable influence on processes of valley fill formation and the associated stratigraphy. The distinctly bimodal, sand/mud mix produced from reworking of deeply weathered granites has allowed significant variability in processes of deposition to be discerned, outlining the dynamic nature of process interaction in this relatively steep upland setting. In non-granitic catchments there may be insufficient textural segregation for the deposits to record such changes in depositional condition, as they may be masked by deposition of massive, uniform units in which only larger-scale cutting episodes are recorded (cf. Prosser *et al*., 1994). Alternatively, given the lack of significant breaks in slope described for other types of upland cut-and-fill floodplains, the range of processes occurring may not be as complex, or as dynamic, as the processes described in this study.

Processes forming valley fills in the landscape of upper Wolumla Creek can be differentiated into two primary sets: those occurring on unconfined valley floor surfaces, and those refilling incised channels. Using the terminology of Schumm (1977), these processes are referred to as downfilling and backfilling respectively. The variable nature of the valley fill stratigraphy of upper Wolumla Creek, and the downstream trends in their material composition, suggest that downfilling processes such as sand sheet or splay deposition on floodplains and in floodouts, and swamp development, have been the dominant forms of valley fill construction. In contrast, backfilling processes are evidenced by channel aggradation and inset features.

The cut-and-fill nature of valley fill deposits in upper Wolumla Creek reflects two scales of material reworking at the base of the escarpment, associated with continuous and discontinuous valley floor incision respectively. Broad-scale cycles of material accumulation and flushing have occurred as part of ongoing landscape evolution associated with escarpment retreat. Continuous valley floor incision reflects knickpoint migration, initiated by downstream controls such as base level lowering (Patton and Schumm, 1975; Schumm, 1980; Schumm *et al*., 1984; Prosser, 1987). Lateral expansion processes following the incision phase may remove virtually the entire fill. In contrast, smaller-scale cut-and-fill processes have occurred through sedimentation processes in floodouts, associated with discontinuous valley floor incision. Such processes are ‘isolated from the rest of the drainage network’ (Schumm *et al*., 1984; p. 53), and are initiated by upstream controls which induce the exceeding of intrinsic thresholds, exemplified by local oversteepening of the valley floor (Schumm *et al*., 1984; Melville and Erskine, 1986), or local weakening of surface vegetation (Schumm *et al*., 1984; Prosser *et al*., 1994).

The schematic model of valley fill incision and aggradation in upper Wolumla Creek (Figure 10) is likely to be a gross oversimplification of reality, as numerous other incision episodes have probably occurred in the last 6000 years. However, stratigraphic evidence for the complexity of cut-and-fill phases has been removed by the present enlarged incised channel. This effect is exaggerated because channels preferentially incise into the pre-existing trench along the dominant drainage line. Hence, evidence for former phases of valley fill incision are generally restricted to the margins of wider sections of the valley, such as those found at tributary confluences. The complexity of channel refilling is evidenced by the present pattern of inset features in Wolumla Creek, with up to four levels present. The origin of these multiple levels has been explained in a model proposed by Hey (1979). If the initial erosional phase is of high magnitude, the resultant oscillation between erosion and deposition is responsible for cut-and-fill, resulting in inset formation. The first erosional phase is characterized by rapid downcutting. Channel bed slopes are initially high and the deposition which follows partially refills that channel. The second erosional phase reworks some of this material and channel slopes decrease. The second aggradational phase partly fills this channel. This occurs recurrently to form a number of laterally discontinuous inset levels. This process is damped through time as the magnitude of the fluctuations is progressively reduced (Hey, 1979). This results from a decrease in sediment output, increase in bed shear stress and decrease in channel bed slope in each erosional and depositional phase.

The specific relationship between phases of valley flushing and infilling and longer-term climatic shifts (*sensu* Rinaldo *et al*., 1995), and notions of landscape stability/instability (*sensu* Butler, 1967; Botha *et al*., 1990, 1994) are yet to be rigorously tested in this landscape setting. As described previously, broader-scale valley flushing episodes before 6000 years BP are in seeming accordance with other studies in coastal NSW and may reflect an extrinsic, climatically driven episode. However, it remains conjectural as to whether these cut-and-fill

landscapes experienced small-scale phases of incision at the same time over the last 6000 years. It has been shown both in Australia (e.g. Young *et al*., 1986; Prosser, 1991; Prosser *et al*., 1994), and overseas (e.g. Graf, 1983; Bull, 1990), that the synchronicity of smaller-scale incision and aggradation processes between different catchments is unlikely, as individual systems respond to a combination of intrinsic and extrinsic thresholds.

It is likely that the present phase of valley fill incision in Wolumla Creek is larger than any other incision phase which has occurred in the last 6000 years. This present incision phase, which has been synchronous across southeastern Australia (e.g. Brierley and Murn, in press; Prosser, 1991; Prosser *et al*., 1994; Herron, 1993), is undoubtedly a direct result of anthropogenic disturbance in catchments since European settlement.

CONCLUSION

Valley fills at the base of an escarpment in upper Wolumla catchment are a type of cut-and-fill floodplain. They demonstrate pronounced downstream variability in their sediment composition, reflecting the interplay of a range of depositional processes which rework materials derived from weathering products of granites from the Bega Batholith. Steeper, upland areas of the valley fill are characterized by thick sand units deposited as sand sheets and splays on floodplains and in floodouts. A few kilometres downstream, muds have accumulated in tea tree swamps or in seepage zones of floodouts. At the transition between these process zones, sands and muds alternate within the valley fill, reflecting shifts in the margins of floodouts and the control influenced by bedrock steps.

Radiocarbon dating of mud units in the valley fill indicate that valley-scale flushing occurred before 6000 years BP. Timing of aggradation is broadly consistent with other studies in coastal NSW and may reflect changed climatic conditions in the early- to mid-Holocene. Aggradation of the main valley fills occurred between 6000 and around 1000 years BP. Around 1000 years BP, the fills were cut by deep, narrow channels. Nineteenth century portion plans, along with anecdotal evidence, indicate that by 1865 the valley floor was intact once more, and formed ‘Wolumla Big Flat’. Anthropogenic disturbance triggered valley fill incision around 1900. Since 1900 valley fill incision, lateral expansion and inset formation have been the dominant geomorphic processes in this upland landscape, releasing significant volumes of sediment from the enlarged incised channel.

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